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Desalination of Coastal Karst Springs by Hydro-geologic, Hydro-technical and Adaptable Methods

Marko Breznik and Franci Steinman
University of Ljubljana, Faculty of Civil and Geodetic Engineering, Slovenia

1. Introduction

The karst landscape consists of rocks such as limestone, dolomite, gypsum and various salts which are, to a greater or lesser extent, soluble in water, and through which underground water flows. According to this, the latest definition of the karst, 10 % of the world's land surface, and as much as 40 % of Slovenia's surface, is covered by carbonate karst rocks, which are the only kind of karst rocks that are important from the point of view of the exploitation of their water resources. On typical carbonate karst, only short lengths of rivers flowing through karst poljes are to be found. Elsewhere, due to the fact that water flows underground, the karst is a dry area, with a lack of drinking water; next to the sea, brackish karst springs are found.

This paper is concerned with the successes and failures of engineering -works which have attempted to improve natural conditions through the construction of various structures for the desalination of brackish springs. The fact that many completed works have been successful should encourage engineers to design and build new hydro-technical structures in karst environments (Breznik, 1998).

In the Ice ages were the differences between the lowest mean temperatures of the cold periods and the highest ones of the warm periods 5 degrees Celsius. These differences between the lowest ones of the Ice ages and the present highest ones are 7 degrees Celsius. During the last 30 years, 10 warmest were between 1990 and 2006. We are living probably in the warmest period during the last 150.000 years (Rošker, 2007). The yearly air temperatures in Ljubljana have increased by 1,7 degrees Celsius in the last 50 years (Kajfež-Bogataj, 2006). Sixty years ago, we had to walk for 1km over the Triglav mountains glacier, after climbing over the Triglav's north wall, 800 m high. This glacier has nearly melted till the present.

Precipitations have decreased from 1100 to 1000 mm/year in the Trieste town during last 100 years. Italian scientists believe that the Azores Island's anticyclone with sunny weather has extended towards the Mediterranean. Precipitations in the Portorož town have decreased by 14%, during the last 50 years (Kajfež-Bogataj, 2006). An about 1000 km large belt of severe drought hazards event extends along the southern Spain, Italy, Greece, Turkey and northern Africa to Syria and Iraq.

Lučka Kajfež-Bogataj, Professor of the Ljubljana University and the Vice-chair of the Working Group II: Impacts, Adaptation and Vulnerability of the Intergovernmental Panel on Climate Change (IPCC), warns that the climate changes will continue and threaten the world population with shortages of water, energy and food. The adaptive measures have to be taken quickly. The proposed desalination of larger karstic coastal springs could provide fresh water for drinking and irrigation (Breznik, 1998; Breznik & Steinman, 2008).

2. Exploitation of karst ground water in coastal areas. Theory with examples

2.1 Sea water intrusion

Brackish karst springs are a regular phenomenon of any seashore consisting of limestone or dolomite. Fresh water from a calcareous karst aquifer is contaminated by the intrusion of sea water, which renders spring water useless. The development of brackish springs, therefore, is of great human and economic importance for areas which are short of fresh water. The first developments were made by the ancient Phoenicians, who covered submarine springs with lead funnels and fed fresh water into leather bags (Kohout, 1966).

2.2 Springs in karst aquifers of isotropic permeability

The porosity and ground water movements in an isotropically permeable karst aquifer, and in an aquifer in granular sediments, are similar. The flow of ground water is of a diffused type. The mechanism of contamination of fresh ground water with sea water in aquifers in sand and gravel has been explained by Ghyben (1888), Herzberg (1901) and Hubbert (1940). Fresh water floats on denser sea water. A 40 m high column of sea water exerts the same pressure at the bottom as a fresh water column about 41 m high. This is known as the Ghyben-Herzberg law. The plane that separates the fresh and sea water in the aquifer is called the interface and is at a depth of about 40 times the height of the fresh water table above sea level.

In areas in which ground water flows towards the sea, some sea water mixes with flowing fresh water and creates a zone-of-mixing some meters high, which replaces the interface. In this zone, ground water is brackish, while above it is fresh water and beneath it unchanged sea water. The mixing process is partly the result of diffusion, but mostly of hydraulic mixing due to the different velocities of fresh and sea water. The thickness of the zone-of-mixing depends on the velocity of ground water movement and the fluctuations of the sea. Ghyben-Herzberg rules can be used for the calculation. Numerous small, brackish springs at small heights of 0.1 to 1 m above or some meters below sea level are typical of such a system. Relevant examples are the lower part of the Postire and Marina Stupin valleys in Croatia and a coastal aquifer in karstic sandstone in Israel. This paper does not discuss such aquifers (Breznik, 1998).

2.3 Springs in karst aquifers of anisotropic permeability

2.3.1 Principle, cases, theory

In the depths of the karst, ground water circulation tends to concentrate along a limited number of well-karstified zones. This is demonstrated by the concentration of drainage in the direction of a few large springs. The karst of the Central Dinaric Alps, with an area of 17,500 km^2, has only 55 large springs. Each spring, with a discharge from 7 to 9 m^3/s, drains a surface of 320 km^2 (Komatina, 1968). A similar situation is found on the island of Crete. Each of three separated karst regions, Dikti, Psiloritis and Lefka Ori, with areas of 150, 300 and 400 km^2, is drained by a single large spring, with respective discharges of 2, 6 and 8 m^3/s. The water collecting galleries, Postire II, Dubrava, Zaton, Gustirne and Blaž, all in Croatia, have also shown a concentration of ground water circulation (Breznik, 1973; 1998).

In an anisotropic karst aquifer, water flows through veins. The form of the veins is not defined: A vein can be a dissolution channel, a permeable fissured zone, a system of small connected cavities, etc. In seeking its course, water erodes paths through the least resistant rocks, so that the veins meander and ramify in many ways. Branching of vein or vein-branching is a place where the primary vein of karst massif branches off into the upper vein leading to the coastal spring and into the lower vein leading to the submarine estavelle. This is the conduit type of ground water circulation in karst. The mechanism of contamination with sea water, therefore, cannot be the same as in karst of isotropic permeability or in grained sediments of uniform porosity and with a semi-laminar diffused type circulation of ground water. In karst of anisotropic permeability, contamination occurs in the vein-branchings. This contamination was first explained by Gjurašin (1943), and in detail by Kuščer (1950), and Breznik (1973, 1978, 1990 and 1998), and Breznik & Steinman (2008).
In 1938, Prof. Gjurašin of Zagreb University developed a theory on the basis of the flow of sea water into the Gurdić spring on the Adriatic coast, that the various specific weights of sea and fresh water are the cause of the sea intruding into springs along the coast and coastal karst aquifers. The conduction channel splits into a larger upper vein and smaller lower vein, the mouth of which must be below sea level. Springs above sea level are only contaminated in a case in which the following equation is fulfilled:

$$\frac{\gamma_m - \gamma}{\gamma} \cdot h_S > h_V$$

where γ is the specific weight of fresh water, γ_m is the specific weight of sea water, h_S is the depth of the vein-branching below sea level, h_V is the height of the spring above sea level (Breznik, 1998). He also illustrated his theory pictorially for three hydrological conditions (Fig. 1; Gjurašin, 1943).

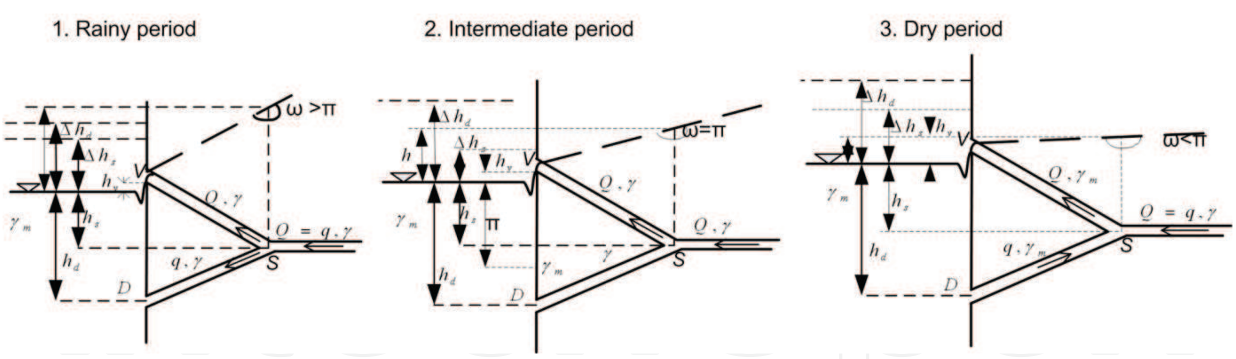


Fig. 1. Outflows of the Gurdić spring in the southern Adriatic (Gjurašin, 1943).

Field observations were performed by I. Kuščer and colleagues in 1938-1940 and in 1947. Seventy coastal and submarine springs, as well as thirty submarine estavelles, were registered near a sawmill at Jurjevo in the Northern Adriatic (Fig. 2). During rainy periods, all the springs deliver fresh water. The discharge of estavelle KEa is 1 m^3/s at a depth of 9 m below sea level. With the discharge decreasing in springtime, the outflow of estavelle KF stops and sea water intrudes into the vein. Estavelle KE and the springs KC and KD are contaminated by 700 mg/1 of CI^-. In July, the springs KA and KB start delivering brackish water. In dry summers, the estavelles KEb and Kola swallow about 0.1 m^3/s of sea water, and the salinity of springs KB increases to 9000 mg/1 of CI^-. The estavelle Kola changes

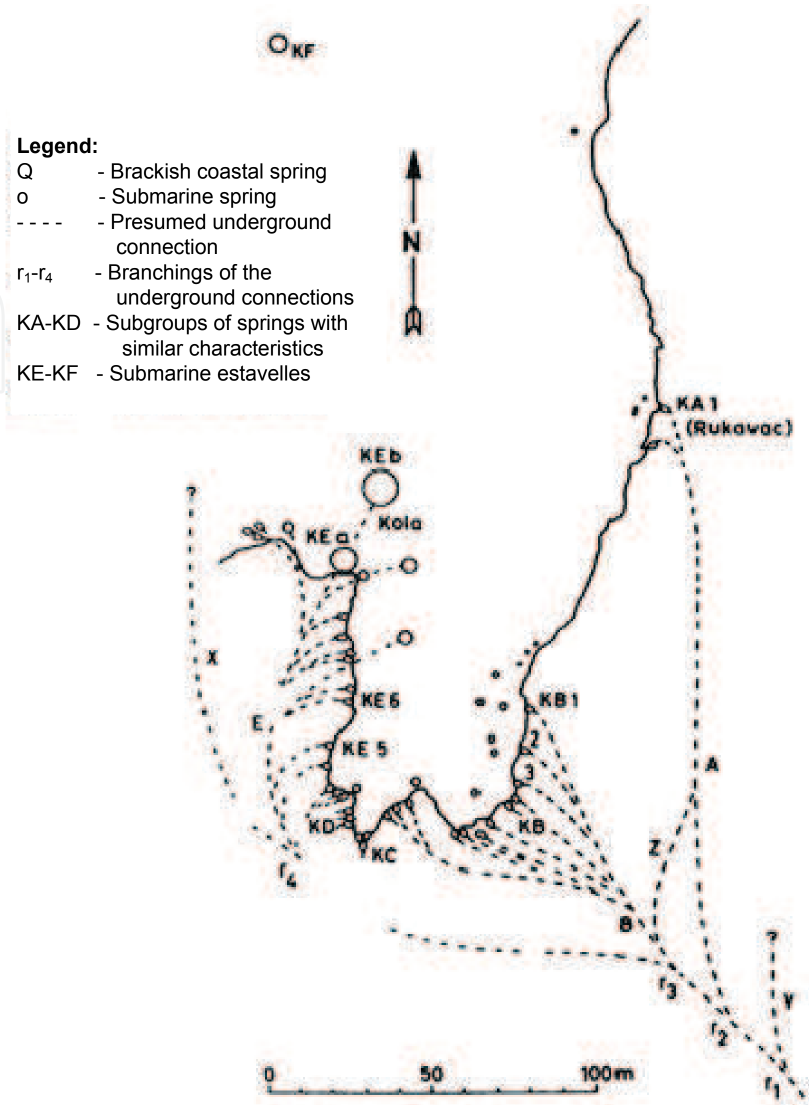


Fig. 2. Jurjevo bay in Northern Adriatic (Kuščer, 1950).

from a spring to a swallow hole very quickly, in 1 to 2 days, and the salinity of the KB springs also increases quickly. After the autumn rains and throughout the winter, all the springs and estavelles discharge fresh water (Kuščer, 1950).

A tracer test with 300 g of fluoresceine was performed on July 30th, 1947. The tracer was poured into the strongest submarine swallowhole, KEa. Colored water appeared after 5 hours in the springs KB, reached the highest concentration after 1 hour, and thereupon slowly decreased. After 6.5 hours, spring KA was also colored by a 2 to 3 times weaker concentration. Kuščer (Kuščer, 1950; Kuščer et al., 1962) indicates in his figure the estimated position of the veins and their important branchings. These field observations confirmed the type of contamination in vein-branchings. This scheme of sea water intrusion into a system of karst conduits is explained on a simplified section with the smallest number of necessary veins (Fig. 3).

Breznik examined the coastal springs and the estavelles in 40 karst places in the former Yugoslavia, Greece and Turkey since 1956 (Fig. 4).

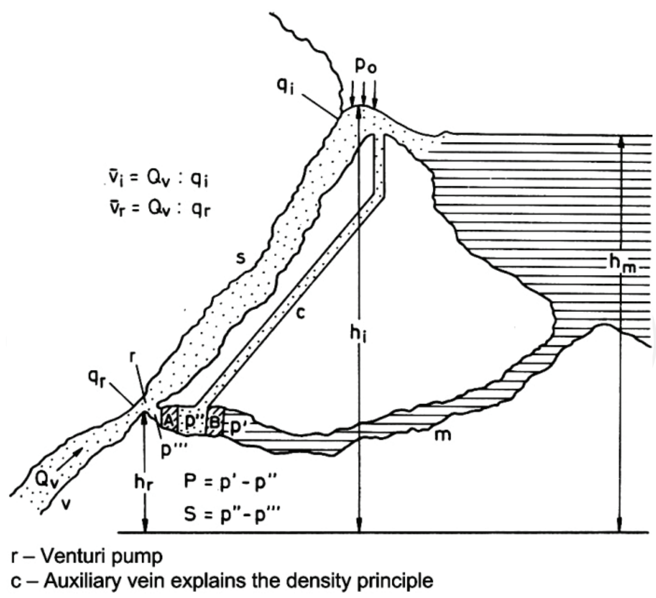


Fig. 3. Coastal spring of conduit type flow in karst aquifer (Kuščer, 1950).

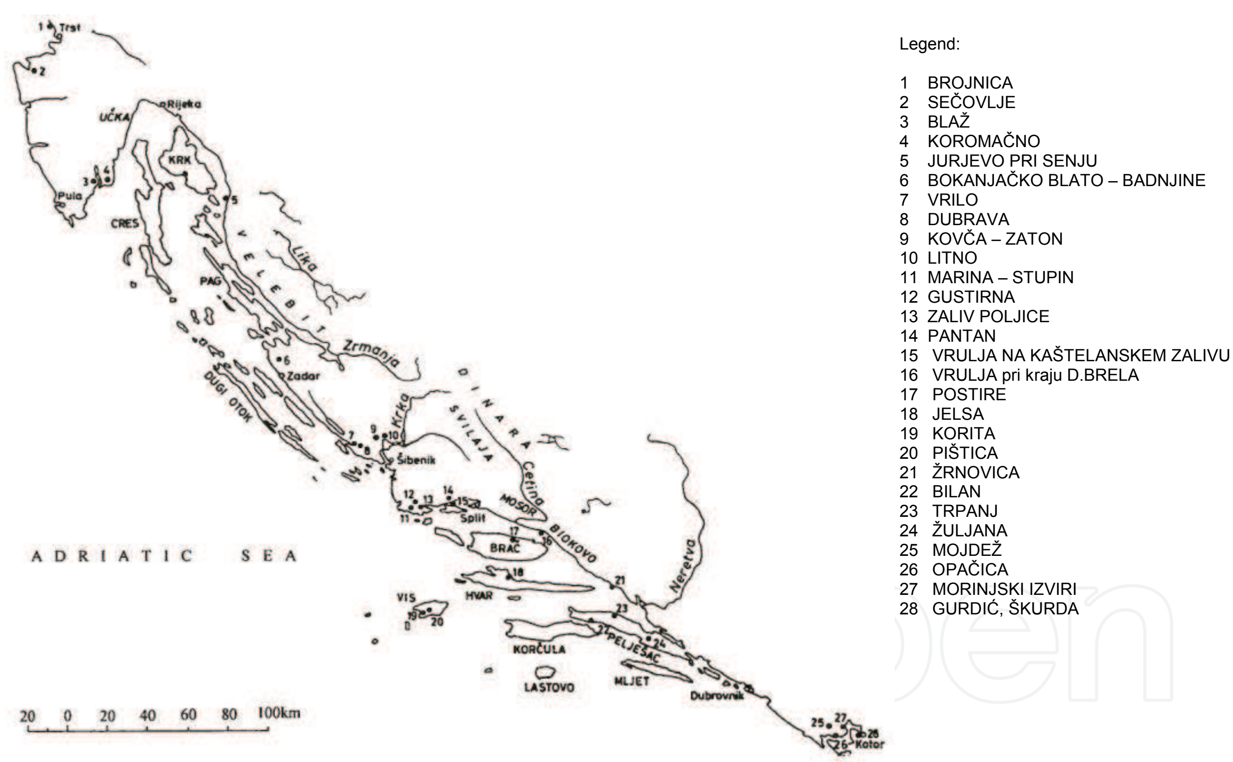
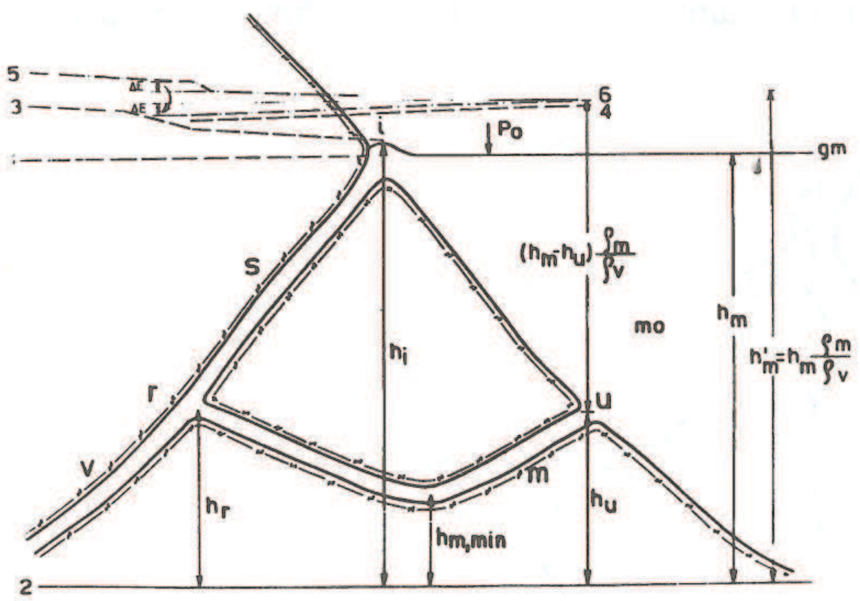


Fig. 4. Investigated karstic coastal springs along the eastern Adriatic coast (Breznik, 1973).

Fresh water from the karst massif is drained through the primary vein. This vein branches off into the lower vein, connected with the sea, and into the upper vein, leading to the spring. The present lower veins were formed in past geological periods by fresh water flowing towards the sea at a lower level, and were primary veins in these periods. Sea water later drowned them, either due to tectonic subsidence of the massifs in the Tertiary to Holocene periods, or due to the melting of Pleistocene ice. The level of the Mediterranean Sea in the Pleistocene period was initially 23 m higher, and then 120 m lower than at present

(Fig. 13). Karst water formed new channels to the actual sea surface, and these are the present upper veins and springs (Breznik, 1998).

All the changes in the direction of flow and salinities are shown in Figs. 7 and 8, whether there is fresh or brackish water in the same coastal spring or submarine estavelle, with either a fresh water outflow or sea water intrusion, are determined in the vein-branchings, and depend on the pressure of water in the veins forming the vein-branching. The piezometric head and density of water in each vein determine the pressure. In rainy periods, the head of water in the primary vein is high, and fresh water flows out of the lower vein as a submarine spring forming characteristic 'wheels' on the sea surface, and out of the upper vein as a fresh water coastal spring. In a dry period, the karst massif is drained and the piezometric head in the primary vein subsides. An equal or slightly higher pressure of sea water in the lower vein enables intrusion of sea water into the vein-branching. Brackish water flows through the upper vein to the spring. The energy for this flow pattern is derived from the fresh water head in the karst massif. Some submarine or coastal springs stop flowing in dry periods, since the fresh water head cannot counterbalance the sea water pressure. In such cases, the vein-branching and the lower part of the primary vein are flooded with sea water. This happens first in deeper vein-branchings (Figs. 5 and 7; Breznik, 1973; 1989; and 1998). Notations used in following figures and equations are shown in Fig. 5.



Legend:
m_0 - Sea
gm - Sea level
i - Coastal spring – brackish water
v - Primary vein with fresh water
r - Branching of veins
s - Upper vein – brackish water
m - Lower vein – sea water
m_{min} - Lowest point of lower vein
u - Mouth of the lower vein
h - Height above some reference level
ρ_v - Density of fresh water
ρ_m - Density of sea water
2 - Reference level
3 - Piezometric head line of the primary and upper veins
4 - Piezometric head line of the lower vein
5 - Energy head line of the primary and upper veins
6 - Energy head line of the lower vein
3-6 - All the heads are expressed through the head of fresh water

Fig. 5. Scheme of veins in the conduit type karst aquifer of a coastal spring (Breznik, 1973).

The pressure at the right side of the vein-branching is expressed by equation (1):

$$p' = p_0 + \left(h_m - h_r - \frac{{v_m}^2}{2g} - T_m \right) g\rho_m = f(Q_m) \tag{1}$$

and the pressure at the left side by equation (2):

$$p'' = p_0 + \left(h_i - h_r - \frac{{v_r}^2}{2g} + T_s \right) g\rho_s = f(Q_s) \tag{2}$$

Sea water can penetrate into a vein-branching if the pressure in the lower vein exceeds that in the upper one. In inequation (3) Breznik (1973) states this requirement:

$$h_i - h_r > \frac{\rho_m}{\rho_m - \rho_s} \cdot \left(h_i - h_m\right) + \frac{\rho_m T_m + \rho_s T_s}{\rho_m - \rho_s} - \frac{v_s^{\,2} \rho_s - v_m^{\,2} \rho_m}{2g\left(\rho_m - \rho_s\right)} \tag{3}$$

All the denominators in the right part of the inequation are differences in densities. The first numerator is the height of the spring above sea level, the second the sum of the head losses in the upper and lower veins, and the third the difference of the velocity heads in the two veins in the vein-branching.

There are certainly very few springs with only three veins, as in Fig. 5 which explains the mechanism of contamination. Many pairs of primary and lower veins, with branchings at different depths, must be expected for a single spring. This might explain the progressive contamination observed in the Almyros Irakliou spring in Greece (Fig. 6; Ré, 1968 in Breznik, 1973).

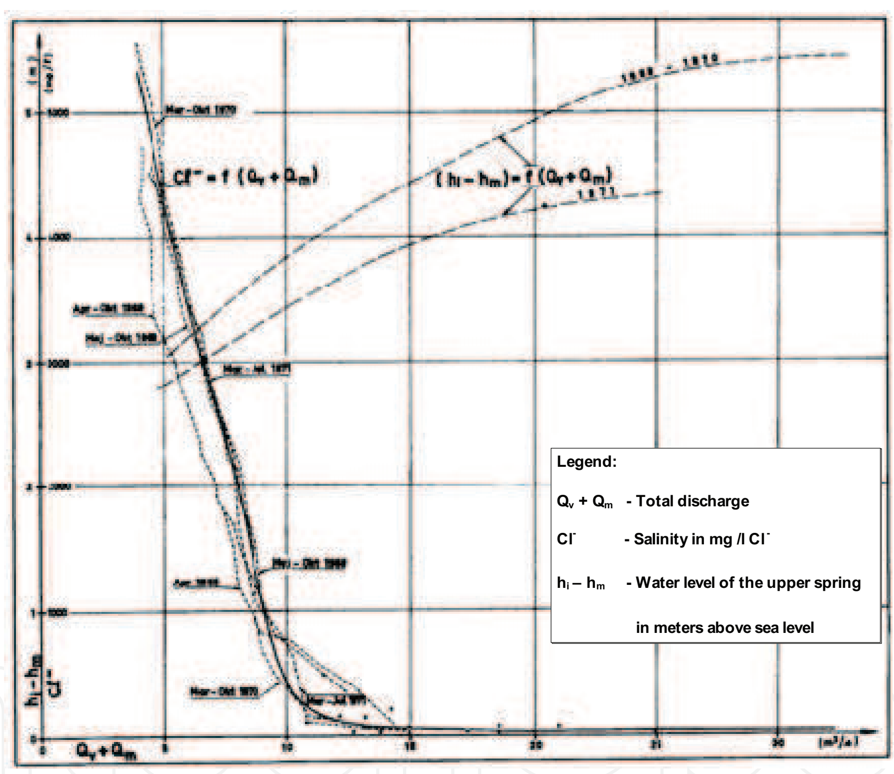


Fig. 6. Almyros Irakliou spring in Greece. Relation between discharge, water level and salinity (Ré, 1968, published in Breznik, 1973).

In rainy periods and during the melting of snow in 2500 high Psiloritis massif, spring water is fresh, with about 50 mg/l of Cl^- at discharges above 12,5 m^3/s. The relation between the discharge and progressive salinity is a curve for discharges from 12.5 to 9 m^3/s, and a straight line for discharges below 9 m^3/s. We can assume that at a discharge of 12,5 m^3/s, the deepest vein-branching starts to swallow some sea water. Shallower vein-branchings start swallowing sea water when the discharge decreases to 9 m^3/s. With smaller discharges, all the vein-branchings swallow sea water. The Almyros spring must have one upper vein, a long lower vein that divides into several channels at its end, some very deep vein-branchings at different depths, and one or several primary veins connected with different vein-branchings. The above system requires a conduit type flow pattern. Many drowned karst channels connected in many directions are a characteristic of a diffused flow pattern that cannot explain the very high level of the Almyros spring in 1977 and 1987 during tests with a spring level by a 1976 dam raised to 10 m ASL.

2.3.2 Equilibrium plane

Many karst springs are fresh during high discharges. When the discharge decreases, contamination begins. Let us suppose the discharge just before the beginning of the contamination is an equilibrium discharge Qeq. The lower vein is already filled with sea water which has not yet penetrated into the vein-branching. There are no losses of fresh water through the lower vein either. Hence

$$Q_m = 0, \quad T_m = 0, \quad \frac{v_m^2 \rho_m}{2g} = 0, \quad \rho_s = \rho_v = 1{,}0, \quad \rho_m = 1{,}028$$

$$h_i - h_r = \frac{\rho_m}{\rho_m - \rho_s} \cdot \left(h_i - h_m\right) + \frac{\rho_s}{\rho_m - \rho_s} \cdot \left(T_s - \frac{v_s^2}{2g}\right) \tag{4}$$

$$T_s = f\left(Q_{eq}\right), \quad \frac{v_s^2}{2g} = f\left(Q_{eq}\right)$$

An equilibrium point in a karst vein filled with fresh water at one side, and with sea water at the other, is the point at which the pressure of sea water is equal to that of fresh water. In a karst aquifer of anisotropic permeability, an equilibrium plane is an interrupted plane that connects all the equilibrium points in the veins. It can be detected only in the veins in which it exists, and is found in very few boreholes (Breznik, 1973).

In a karst aquifer of isotropic permeability, or in an aquifer in granular soil, the sea water zone is separated from the fresh water zone by an interface, or a zone-of-mixing. The interface and the zone-of-mixing are continuous planes and can be detected in all boreholes in the area. The difference between an interface and an equilibrium plane is similar to the difference between the ground water table of a phreatic aquifer and the piezometric surface of a confined one. The first can be detected in any borehole in the area, while the second only in boreholes which have penetrated into the confined aquifer.

The elevation of the equilibrium plane changes in accordance with the elevation of the piezometric surface of fresh water. In rainy periods, the piezometric surface of fresh water is in a high position and the equilibrium plane in a low one. Fresh water flows out of the lower vein as a submarine spring and out of the upper vein as a coastal spring. In this period, the equilibrium plane is below the vein-branching and below the lower vein (Fig. 7, Phase A).

During the decline of the discharge, the piezometric surface of fresh water subsides and the equilibrium plane consequently rises (Phase B). When the equilibrium plane crosses the vein-branching, sea water from the lower vein intrudes into the vein-branching (Phase C). Brackish water fills the upper vein and flows out of the coastal spring. In the dry period, the piezometric surface in the karst massif continues to subside and the equilibrium plane in the coastal zone rises. When the equilibrium plane has risen above the vein-branching and crossed its primary vein, the outflow of fresh water through this vein-branching is blocked (Phase D). Fresh water drained from the karst massif flows through higher vein-branchings and is there contaminated. On the surface, we observe these phenomena in dry periods as a decrease in discharge of all springs, some coastal springs dry out, all submarine springs stop flowing, all submarine estavelles start swallowing sea water, and all springs deliver brackish water (Breznik, 1989; 1998).

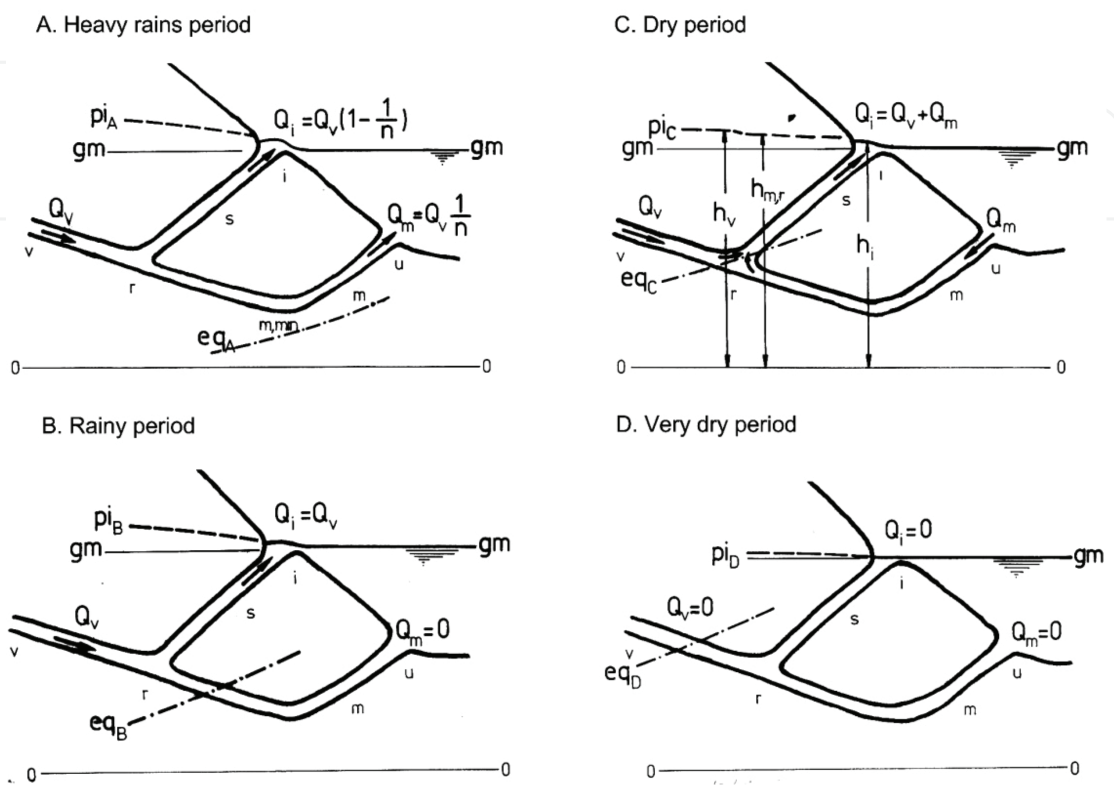


Fig. 7. Coastal spring with a siphon-like lower vein in a karst conduit flow aquifer, pi - piezometric surface, eq - equilibrium plane. Four Flow: Salinity regimes (Breznik, 1989; 1998).

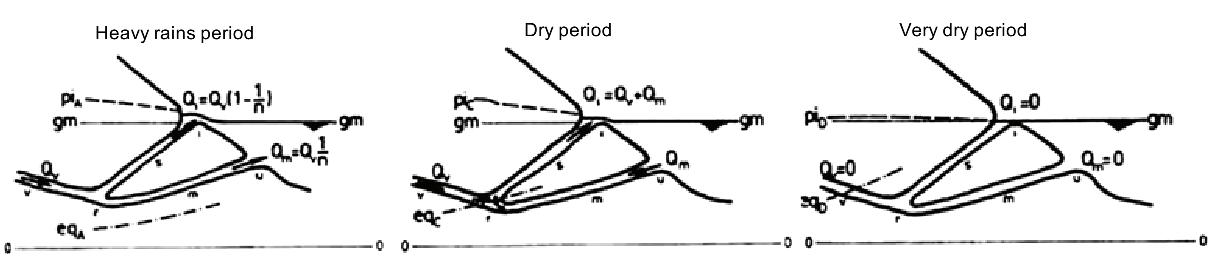


Fig. 8. Coastal spring with a rising lower vein in a karst conduit flow aquifer. Three Flow: Salinity regimes (Breznik, 1989; 1998).

There are certainly very few springs with only 3 veins. Many pairs of primary and lower veins, with the branchings of different depth, must be expected for a single spring. This explains the progressive contamination observed in the Almyros spring (Fig. 6).

2.3.3 The case of the 'Sea mills' on Kefalonia Island

Sea water flowing into swallow holes of the 'Sea mills' on Kefalonia Island in Greece was marked with 100 kg of uranine in 1963. The total inflow of sea water was about 1.7 m^3/s and

the brackish outflow of the Sami springs about 20 m^3/s. The brackish water of these springs contained from 10 to 12% sea water. The tracer reappeared after 16 to 23 days.
The distance between the mills and the Sami springs being 15 km, the mean velocity of tracer movement was 1 cm/s (Fig. 9). Glanz (1965) was of the opinion that this sea water intrusion of 1.7 m^3/s could not be ascribed to a Venturi-tube suction effect, because such an arrangement, together with the simultaneous dissolution of calceros Venturi pumps, would be too complex to resist under natural conditions. He explained the inflow of sea water by a natural injector effect of fresh karst water submersed in sea water, working on the principle of a water jet pump. A physical model supported that explanation (Fig. 10, Glanz, 1965; Fig. 11, Maurin, 1982). The phenomenon of the 'Sea mills' could be more easily explained by mixing in a deep vein-branching on the different densities principle (Breznik, 1998; Fig. 12, Breznik & Steinman, 2008).

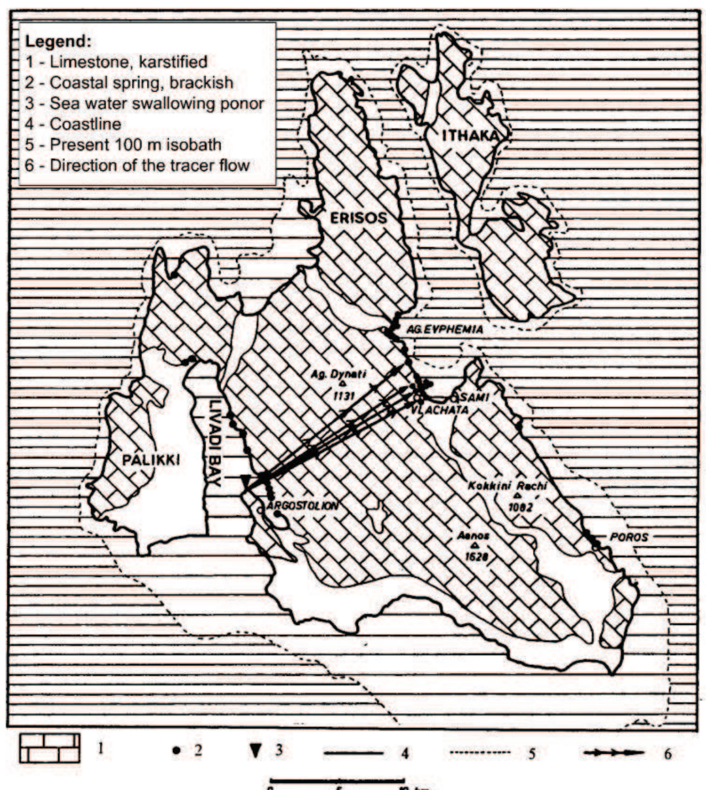


Fig. 9. Kefalonia Island in Greece. Ponor of sea water near Argostolion (Glanz, 1965).

Many terrain observations talk against the hydro-dynamic method of infusion. A flow of sea water has been noted in summer in the lower part of the source channel of the Port Miou springs in France. Even the construction of underground desalination barriers in the spring was not entirely successful, since source water still contained around 4000 mg/l CI. Further development of the springs was then abandoned.
A similar phenomenon, i.e. a powerful inflow of sea water into the estavelle on the floor of the gulf of Bali, and thus into the coastal karst aquifer, was observed in the summer of 1991 and the outflow in October 1970 and May 1983 on the island of Crete (Fig. 18).
All the above springs have fresh water in rainy periods and cannot have been contaminated by a hydrodynamic effect, which should be greatest at high discharges. These springs are contaminated in the vein-branchings in conduit flow aquifers because of different densities

of sea and fresh water. The vein-branchings can be deep in coastal karst aquifers, which is partially a result of the 120 m lower sea level in the Pleistocene period (Fig. 13) and partially the effect of inflow of sea water into deep syphons (Figs. 22 and 23).

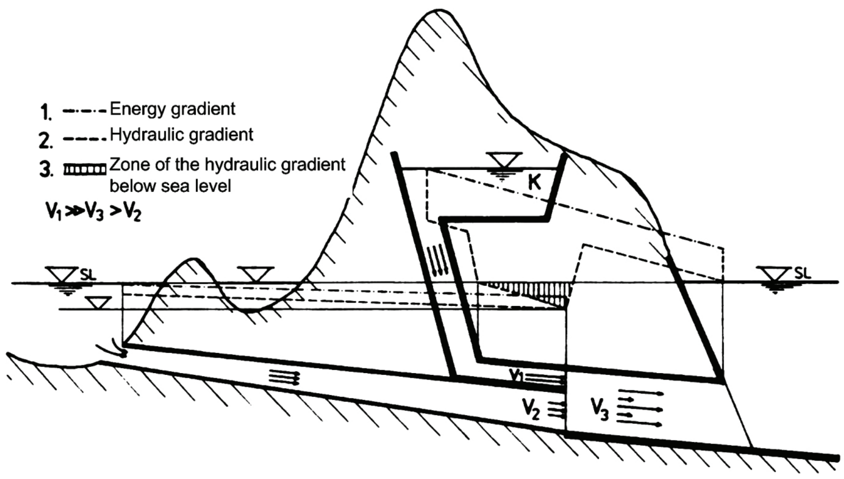


Fig. 10. "Sea water mill" on Kefalonia Island in Greece (Glanz, 1965).

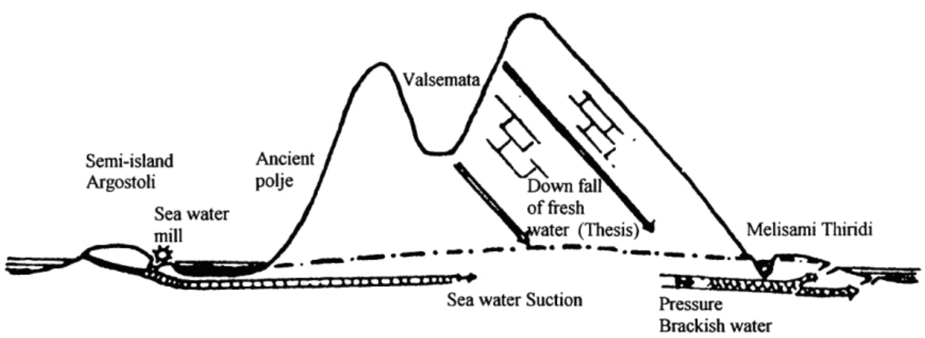


Fig. 11. Scheme of hydro-geological water circulation in the karstic rock mass of Kefalonia Island (Maurin, 1982).

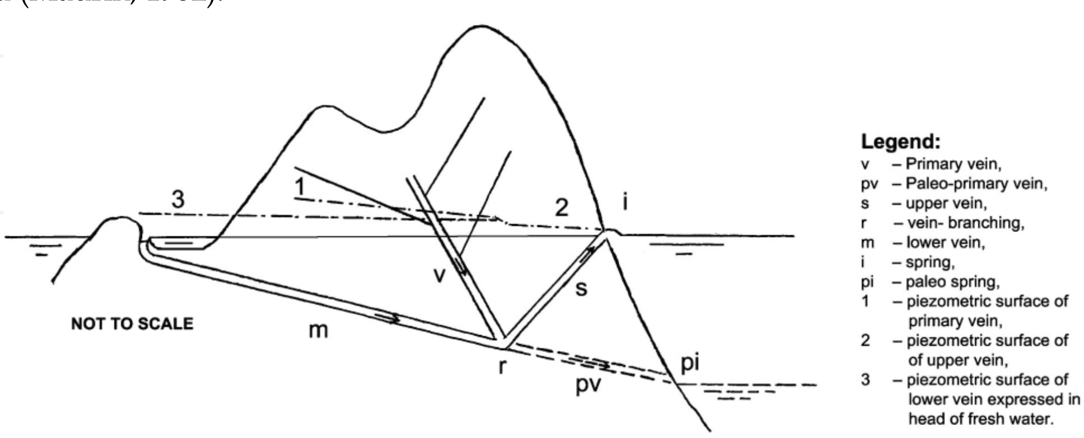


Fig. 12. "Sea water mill" on Kefalonia Island in Greece, explained by the different densities principle (Breznik & Steinman, 2008).

The consequence of deep vein-branching is high salt water contamination in dry periods, of springs such as Almyros Irakliou 10 m above sea level, Kournas lake 17 m and

Annavaloussa 12 m, on the island of Crete and Pantan 4 m in Croatia. The hydrodynamic method of salination cannot explain such high level of contaminated springs in dry periods, and this is the major indirect evidence of the method of contamination by the different densities of fresh and sea water, in deep vein-branchings in coastal conduit flow karst aquifers of anisotropic permeability (Breznik, 1973; 1998).

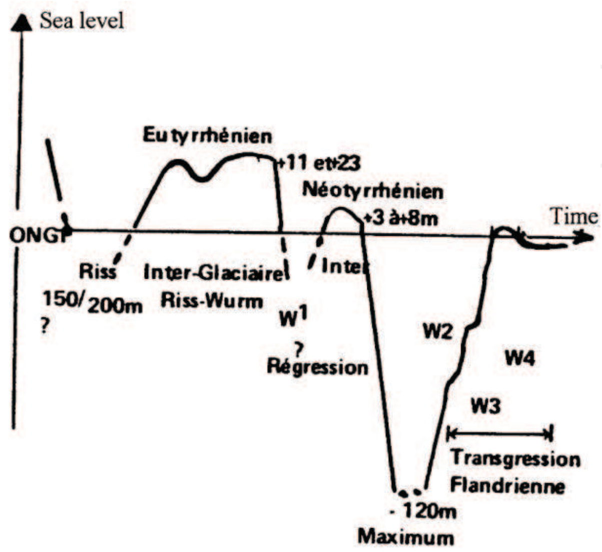


Fig. 13. Fluctuations of sea level in the Pleistocene period (Bonifay et al., 1974).

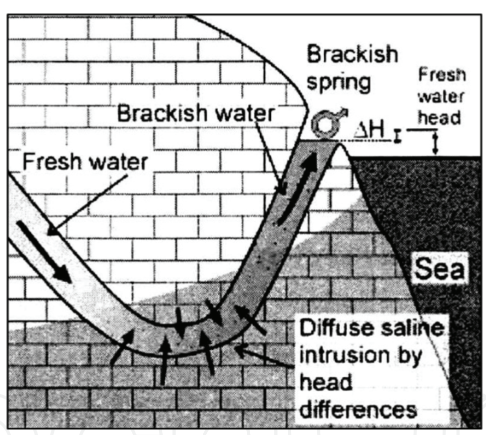


Fig. 14. Brackish spring contaminated by a diffuse saline intrusion in the main conduit (Arfib, 2005).

In the Pleistocene period was the sea level till 120 m deeper and the Livadi bay on Kefalonia Island, with a 30 m deep sea now, a karstic polje with a ponor and an outflow to the Sami coast. This paleo-primary vein is a lower vein now, and with a vein-branching at 100 m BSL. We can easily explain the inflow of sea water into the "mill ponor" by the different densities of fresh and sea water. The 100 m deep column of sea water in the vein-branching provides a 2,5 m rise of the piezometric head, expressed by the head of fresh water. Out of this are 0,8 m losses of the head, used for the flow of sea water through the 15 km long lower vein and 1,7 m is the denivelation of the sea level below the mill (Breznik & Steinman, 2008).
In the Arfib’s one vein karst system, it would be difficult to explain a change from the outflow to the inflow of the estavelles during 1 to 2 days in the Jurjevo bay (Kuščer, 1950).

Also a 20 to 30 m high rise of the Almyros spring level would be an utopian proposal (Breznik, 1984 b; 1989).

2.3.4 Investigations

In such natural conditions, explorations are difficult and have to be scheduled by stages, with the less costly in the beginning and expensive ones undertaken only for important and promising springs. The first investigations include observations and recording of all natural phenomena over the course of a year. Discharge, salinity and duration of flow of coastal springs, intensity and duration of flow of submarine springs, and meteorological processes in the recharge area, must be observed. The second stage of explorations comprises measurements of spring level, discharge and salinity. Relations among discharge: salinity: level must be known for different periods of the year (Arandjelović, 1976).

The third stage of explorations must already be oriented towards the most promising development technique. For the 'isolation of fresh water from sea water method', geophysical measurements, drilling and salinity detection in boreholes have to ascertain the position and depth of the lower vein, which must be sealed. Tracer tests are also sometimes useful. Reliable values of salinity in boreholes are obtained only by 'bottom point' measurements, which means in boreholes with their casing open at the bottom only. It is not possible to distinguish between fresh and sea water zones in boreholes with a casing perforated throughout its length, because of the flow and mixing of water inside the casing.

For the 'interception of fresh water inside a karst massif method', trace lines, or lineaments, of karst and tectonic phenomena on the surface indicate the direction of underground water circulation. Fractured zones identified from aerial photos or satellite pictures may be chosen as favorable locations for drainage galleries or wells.

For the 'rise spring-level method', several discharge: salinity: level curves are needed, specifically for the original natural conditions, and for the conditions created by an artificial rise of 3 to several meters in spring level. Observations of the piezometric level in the recharge area of the spring during different periods of the year could give clues for ascertaining the depth of the vein-branching. A detailed program of exploration must be prepared and later modified according to the results obtained. For each proposed method of exploration, the program must be determined in advance: what is the aim and what are the possible results. The idea of 'let us explore and later see what that brings' consumes time and funds (Breznik, 1998).

The fourth stage of investigation starts with a partial and provisional construction of the proposed development structures. Their adaptability has to be foreseen in the program because final success can never be assured in advance by the first three stages only.

3. Methods of the desalination

3.1 Hydro-geological interception method

The idea of this method is to capture fresh water inside the karst massif, outside the present sea water influence. Successful are the deep drilled wells Klariči in Slovenia with 0,25 m^3/s, the system Zvir II with the dug and the drilled deep wells with 0,6 m^3/s in Croatia, Gonies and Krousonas deep wells in Greece and elsewhere. Unsuccessful are due to overexploitation and salination the deep wells in Tyllisos and Keri areas in Greece, many drilled deep wells in the Murgia, Salento and Taranto coastal aquifers in the southern Italy and in other places (Pavlin, 1990).

3.2 Hydrotechnical isolation method

The idea is to prevent the inflow of sea water into the karst massif by a diaphragm wall or a grout curtain. Positive examples are the grout curtains for the Žrnovica and Bačvice springs in Croatia and negative the grout curtain for the Tabačina spring in Montenegro, the diaphragm wall for the Malavra spring in Greece and the others (Breznik, 1998; Nonveiller, 1989; Vlahović, 1983).

3.3 Hydrotechnical rise-spring-level method

The idea of this method is to prevent the inflow of sea water by raising the spring level by a dam, a grout curtain or a diaphragm wall. This method could succeed only in an aquifer with a siphon shaped lower vein. But also there a too high rise could induce the losses of fresh water through the lower vein into sea, shown on Fig. 7 from the period C by a human rise of the spring level to the period B, and not by a to high rise, to the period A (Breznik, 1971, 1973; Breznik & Steinman, 2008).

3.4 Adaptable method of the reduced pumping discharge in dry periods

In many coastal aquifers a reduced pumping discharge could maintain a low salinity of water in the dry periods. A reduction of pumping prevents the salination of the drainage galleries Kovča - Zaton, Roman wells (Bakar, Trogir), Šipan in Croatia (Biondič, 2005), and Klariči in Slovenia (Breznik, 1998; Breznik & Steinman, 2008; and elsewhere) during the dry periods.

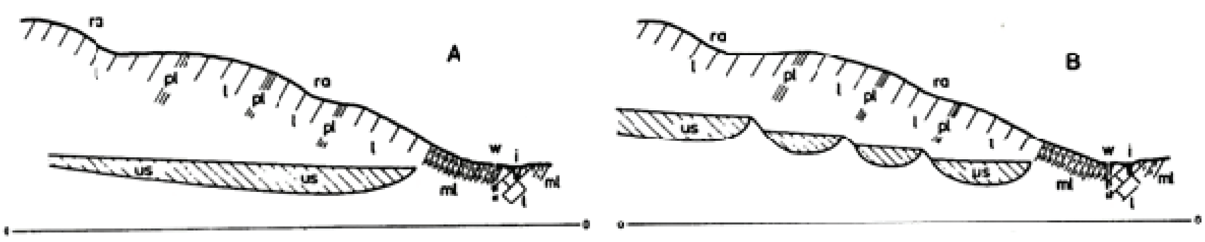
4. Cases

4.1 Investigation of the underground storage of the Rižana spring

The municipal water supply of the town of Koper in Slovenia, from the Rižana karst spring, was constructed 50 years ago. Observations over a period of about 100 years are available. The mean discharge of the spring is about 4 m^3/s, the maximum is about 80 m^3/s, the annual minimum 0.27 m^3/s and the absolute minimum 0.11 m^3/s, measured in 1921 after two very dry years. There is now a suggestion to increase the exploitation over the annual minimum, by over pumping the underground storage in dry periods. The recession curves of the spring discharge have indicated an underground storage of 7 million m^3 which has regulated the outflow at the present spring level. Several analyses using the stable isotopes deuterium and ^{18}O have ascertained a retention time of 4 months between winter precipitation and the outflow of this water the following summer. This pointed to a large underground storage of over 30 million m^3.

The Vaclusian type spring on a small limestone plateau is separated by a 1 km wide layer of marls from the main recharge area, an imbricate structure of about 180 km2 in limestone. The spring is at an elevation of 70 m above MSL and the recharge area is at 500 to 1100 m above MSL. Exploitation of this additional underground storage is possible only by lowering the present water table to a lower level in dry periods. In spite of this very clear principle, it is not clear where and how to capture water from this storage that is, at present, dead storage of the spring. In the event of this storage being a constantly rising water table, of it being uniform over a large area and connected with the spring by a deep siphon, it would be possible, during the dry period, to pump water out of the existing deep wells in the spring area.

A more probable supposition is that there are various dead storages at different levels, subdivided by either less permeable rock steps or contracted conduits. In such a case, each storage has to be captured by separate drainage tube wells, or a drainage gallery with a water gate and an access tunnel. We have noted that the locations of the underground storage are not known in advance (Fig. 15). They must be searched for individually, and individual deep wells drilled in each case for test pumping in dry periods. Eight new deep wells were built, with a total capacity of 0.92 m^3/s, at distances of 0.5 to 1.5 km upstream from the spring. In the dry summer of 1993, pumping began from the underground storage at a rate of 0.39 m^3/s from the wells, and a further 0.16 m^3/s flowed from the spring. Because of the rapid lowering of the water surface in the wells, by about 10 m, pumping had to be reduced after a few days to 0.15 m^3/s. The volume of the underground storage in the Podračje imbricate structure was assessed at about a quarter of a million m^3 of water. About 10 million m^3 of accumulated underground water are needed to increase the minimum flows of Rižana for some months. Since speedy solutions were required, we proposed that further exploration of this source be abandoned for 25 years (Breznik, 1993; 1998).



Legend :

A - Undivided reservoir
B - Divided reservoir, with cascades
ra - Recharge area
l - Limestone, Cretaceous
pl - Plated limestone, dolomite, marlstone, Paleocene-Eocene
ml - Marlstone, sandstone, Eocene
us - Underground reservoir
w - Deep-well
i - Rižana spring
o - Sea level

Fig. 15. Rižana springs in Slovenia. Possible type and situation of karstic underground reservoirs (Breznik, 1990; 1998).

4.2 Kras coastal aquifer in northern Adriatic

The surface of the Kras aquifer is 730 km^2, with a larger part in Slovenia and a coastal outflow area in Italy. Recharged is by the infiltration of the precipitations of 1100 mm/year, by the Notranjska Reka with 5 m^3/s (lowest measured: 0,18 m^3/s only) inflow in the ponors near Škocjan, by 1 m^3/s inflow in the ponors of the Vipava River and by the Isonzo (Soča) river ponors buried beneath gravel along the Doberdo karst. The mean outflow is 35 m^3/s in rainy periods and 10 m^3/s in dry periods - the majority of it in the Timavo springs area, a small part of 0,2 m^3/s out of small coastal springs and an important out of the estavelles in the Duino sea, which swallow sea water in the dry periods (Petrič, 2005; Steinman, 2007; Breznik, 2006).

In the Klariči pumping station 3 deep wells, VB-4 from 16 m ASL to 54 m BSL, were drilled near the B4 borehole and fresh water captured in a karst conduit of 1,3 m at a depth about 25 m below sea level (Krivic, 1982). The Klariči station with a limited pumping discharge of 250 l/s supplies drinking water to the Kras region with 25.000 people since 1986 and till 130 l/s of water is flown in dry periods to the Slovene coastal region with 40.000 people since 1994. Coastal region has also the Rižana karst spring with only 200 l/s m the dry periods (Petrič, 2005). Fresh water demand of the coastal region is 500 l/s in summer (Bidovec, 1965; Krivic and Drobne, 1980; Steinman et al., 2004; 2006; 2007). The level of the main Timavo spring was risen about 1,5 m ASL with a small weir and was the main water source for the Trieste town until 30 years ago.

The lowest static water level in Klariči was 2,5 m ASL. Karst ground water pumped in Klariči is recharged in the eastern part from the Kras during rainy periods and from Isonzo river ground water mainly during dry periods. Isonzo river ground water infiltrates in paleo-ponors buried beneath gravel in the NW part of the Doberdo karst plateau. Three large estavelles about 1 km from the Duino (Devin) coast, are the main outflow of this water in rainy periods, and swallow sea water in dry periods. They were important springs of a part of the Isonzo river in a dry upper Adriatic land during the Lower Pleistocene (Šegota, 1968). The estavelles indicate a geologic border on sea bottom between the karstified carbonate rocks of the Cretaceous against impervious Flysh sediments of the Eocene (Breznik & Steinman, 2008).

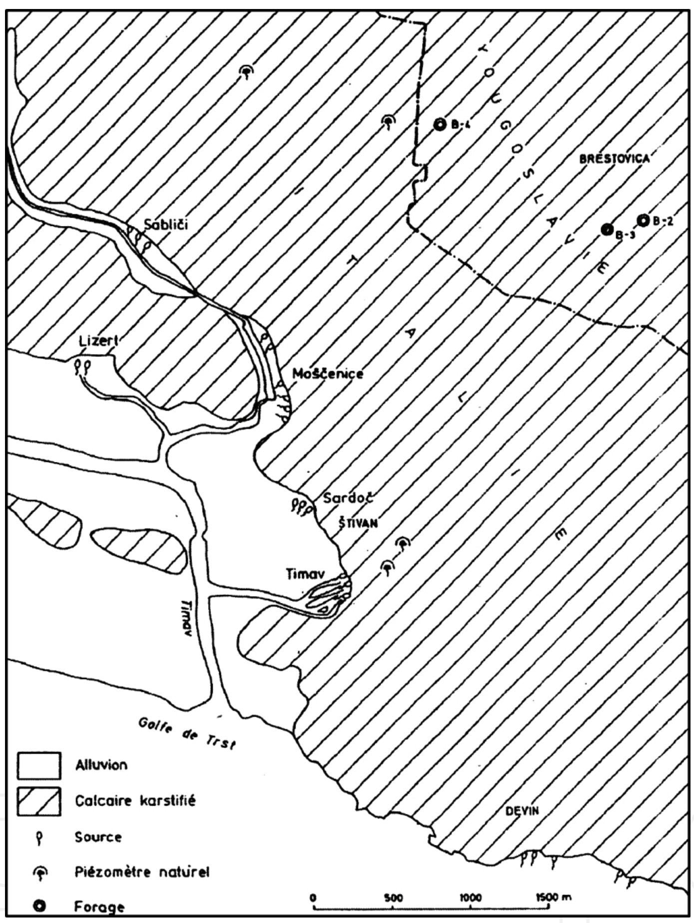


Fig. 16. Outflow area of Kras aquifer (Krivic, 1982).

How sustainable are good quantity and quality of this water? We explain these in Klariči station at 4 km from the coast and water pumped out a karst conduit at 25 m below sea level, by a human raised level of the Timavo spring, by a large outflow of Timavo springs of 10 m^3/s in dry periods, by a shallow karstifications due to an impermeable Flysh barrier on sea bottom of 20 m BSL at the outflow of the estavelles, by a low permeability of the karst rock mass of a conduit and by a chance of an absence of the human pollution until now.

Land reclamations in the Timavo springs area, f. e. for new storage places of the shipyard, with drainage ditches and a destruction of the small weir would lower water level there and also in the Klariči station and could induce a salination of water.

Mercury ore was excavated in the Idrija mine, which is closed now, for 500 years. Idrijca and Soča rivers transport 1500 kg of Hg to sea every year, washed out of old mine's deposits. In water pumped out of VB4 well in Klariči 1,2 ng/l of Mercury was measured. This very small quantity of Hg is not harmful for the health, but could accumulate in the cave deposits (Doctor et al., 2000). A third threat could be human pollution as there are no protection areas.

We propose to pump 2-3 m³/s of the Rižana river to a 100 m higher large Dragonja storage reservoir in the rainy period and to flow it out in the dry periods to Rižana with an existing drinking water treatment plant and towards the pipeline from the Gradole spring in Croatia, where the contract of an obligatory water supply has expired in 2005. The elevation of water in Dragonja reservoir at about 170 m ASL enables always a gravitational outflow to the supply system without electricity. In the dry periods, could be the lower layer of euthropic water of Dragonja reservoir released, in cascades enriched with oxygen and used for the irrigation of Dragonja and Sečovlje plains, what is a 25 years old proposal. The mixing of reservoir water, with the aim to prevent eutrophication, will not be necessary. Two inflows of water, from the northern Rižana and southern Dragonja directions, into the coastal water supply system, will increase its safe operation.

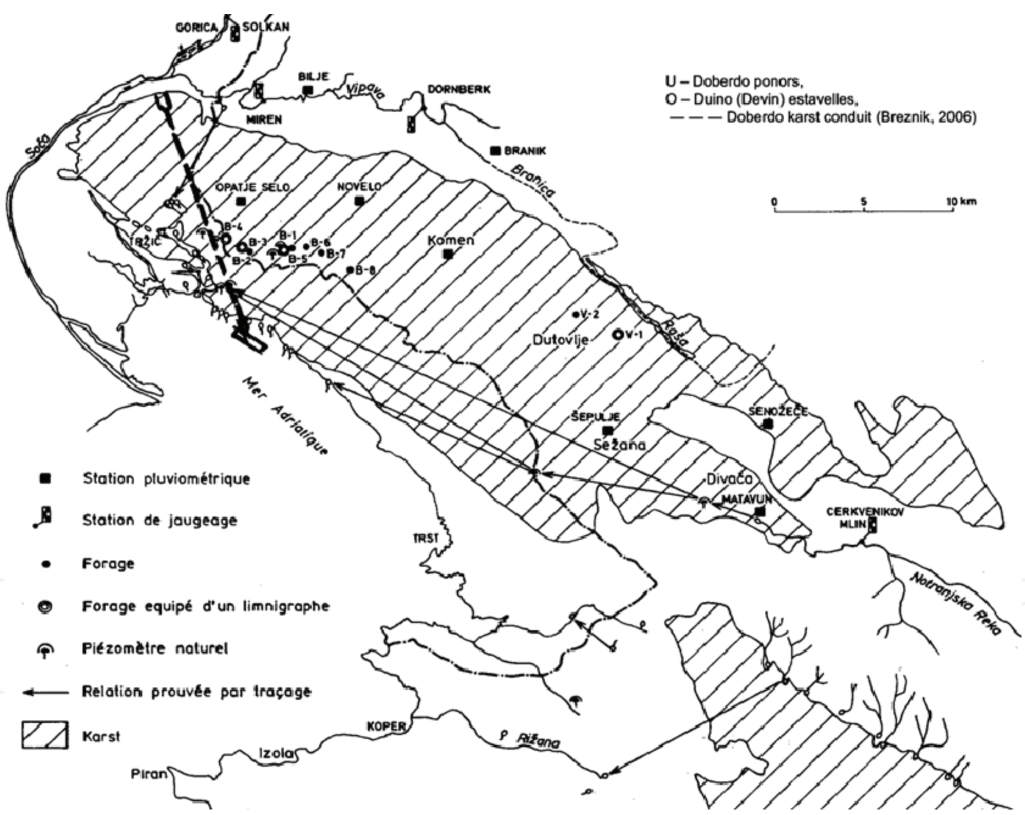


Fig. 17. Doberdo karst conduit (Breznik & Steinman, 2008), Kras aquifer (Krivic, 1982).

The proposed, and designed new Padež or Suhadolca storage reservoirs with a 35 km long new pipe-line, will be "on the other side of the hill" and will need a 250 m high pumping, all around the year. The electrical energy is however not always at disposal as few-days-lasting black outs in 2006 and 2007 in California, New York and Western Europe have demonstrated. These reservoirs would need also an artificial mixing of water with the aim to prevent eutrophication (Breznik & Steinman, 2008).

4.3 Bali bay coastal aquifer in Greece

The catchment area of the Bali bay aquifer is the Talea Ori karstic massif with 50 km2. In the wet period fresh water flows out of coastal springs and estavelles in the Bali bay (Economopoulos, 1983). We explored Syphona spring No 3 at 12 m BSL with an outflow of some m^3/s of brackish water with around 10.000 mg/l CI in the late summer of 1970. Divers led by P. Economopoulos were hampered by poor visibility in the outflow funnel of the spring, what indicates the mixing of fresh and sea water there (Breznik, 1998). French divers studied estavelles-ponors in the Bali bay in late summer 1991. At a depth of 12 m there were a number of smaller and 3 larger estavelles which swallow more than 1 m^3/s of sea water (Barbier et al., 1992). Position of estavelles in the wet period and the outflow of the Syphona spring in the dry period indicate the direction of the Talea Ori underground flow. Geophysical methods: Map of electrical potentials "mise à la masse" with one electrode in the Syphona spring and the Very low frequency (VLF) of radio waves (Mueller et al., 1986) should determine the position of the main Talea Ori water conduit to the Syphona spring (Breznik, 1998; Breznik & Steinman, 2008).

The next exploration works are: capture ground water of the conduit with drilled interception wells; excavate a ditch with a regulation valve from the interception wells to sea at 2 m ASL; plug with a concrete and a grouting the conduit between the interception wells and the Syphona spring; construct a one row grout curtain, distance of the boreholes 2-3 m, till 60 m and 120 m BSL; rise the water level by the regulation valve to 5 m and 10 m ASL; find out possible water losses along the coast by registration of new springs and by the temperature logging of coastal water from a helicopter; construct additional grout curtains if necessary.

We evaluate there is a 70% probability to desalinate 0,5 to 1,0 m^3/s of the Talea Ori ground water that could be used in the Rhetimnon city area.

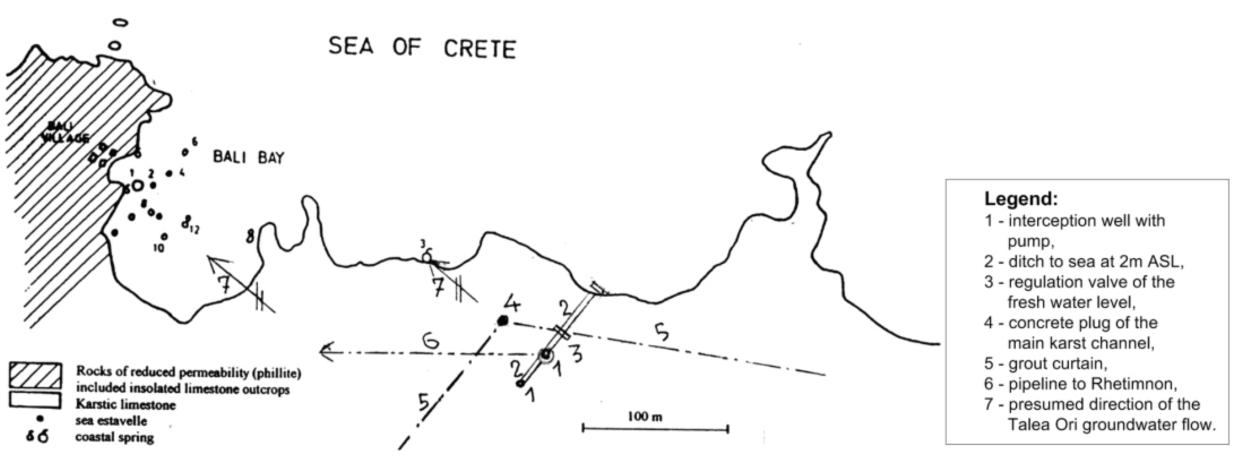


Fig. 18. Structures for the desalination of the Bali bay springs and estavelles (Breznik & Steinman, 2008). Bali bay springs and estavelles (Economopoulos, 1983).

4.4 Anavalos-Kiveri coastal springs in Greece

Tripoli and other poljes are drained by coastal and submarine springs along the NE coast of the Peloponnesus peninsula in Greece (Gospodarič et al., 1986). A 180 m long semicircular dam was founded on calcareous breccia at 10 m BSL and with a top at 4 m ASL in 1968. We visited the place in the spring 1969. The sluices of the dam were open and a river of greenish color flowed out, that clearly differed from the blue sea. We observed a typical circle of ground water flowing out of an estavelle at a distance about 0,5 km.

Prof. Ständer from Germany, who proposed the isolation of springs, answered in a letter that a major development was achieved by the isolation of the springs area with the dam, thereupon the salinity decreased to 200-300 mg/l CI. A second phase of the development was completed with a rise of the pool level to 3 m ASL at a discharge of 12 m^3/s and the inflow of sea water stopped (Ständer, 1971). A photo shows a present outflow of ground water outside the Kiveri dam (Lambrakis, 2005). The average springs discharge is 6 m^3/s. During the irrigation periods 1955-1990 the ground water quality worsened due to the over pumping and the sea water intrusion (Monopolis et al., 1997; Tiniakos et al., 2005).

A short analysis of the available data indicates that the isolation of the Kiveri springs against sea water inflow is not completed. A dam founded on much karstified breccia without a consolidation of the limestone mass and without a grout curtain, is not a completed structure. Prof. Ständer estimated the depth of the karstification at 90 m BSL. We suppose this depth to be either 30 m deeper of the sea bottom at the estavelle observed in 1969, or 30 m deeper than a 120 m BSL deep sea level in the Pleistocene if the Argos bay is deep enough (Breznik, 1998; Tiniakos et al., 2005).

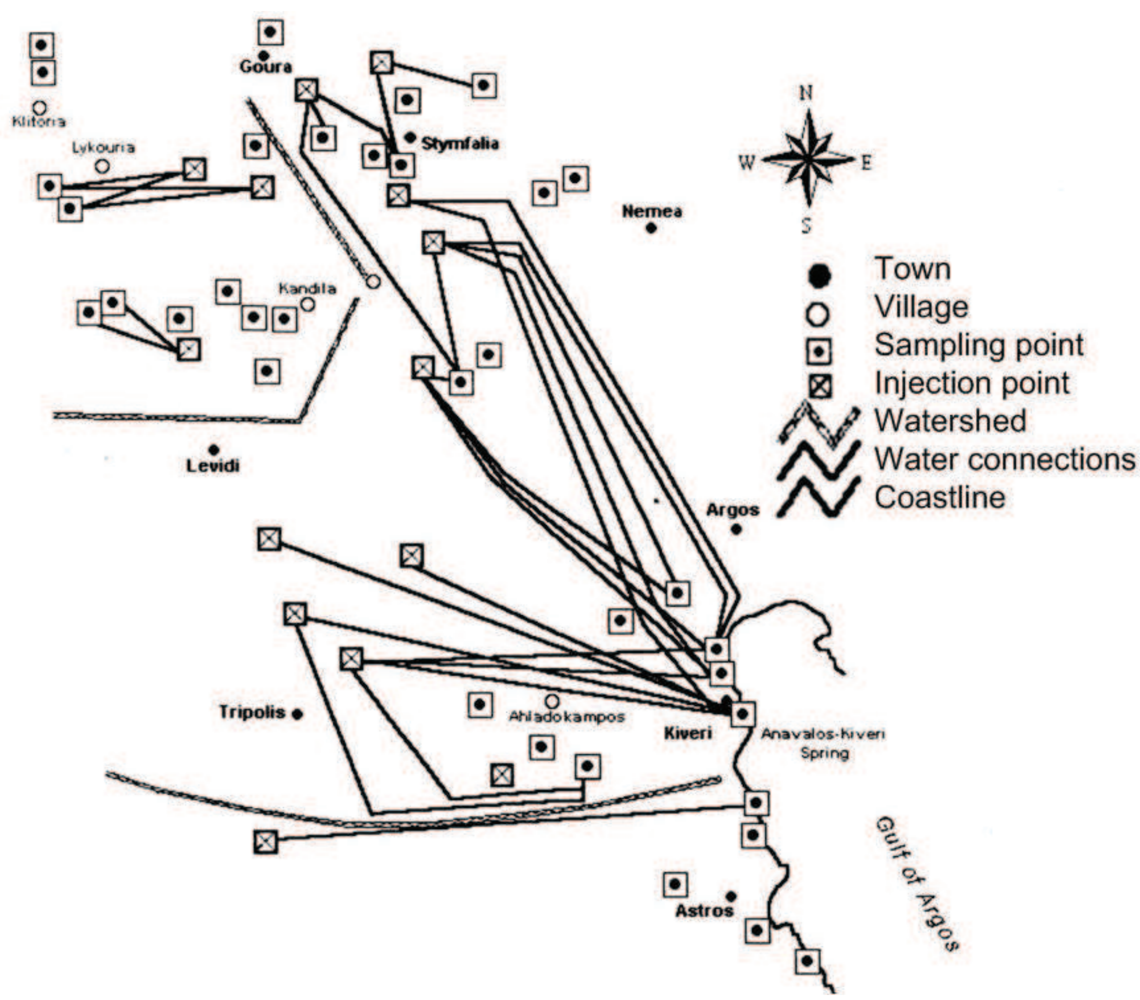


Fig. 19. Underground water connections of the Peloponnesus, found by tracing experiments (Gospodarič & Leibungut, 1986).

We propose to prevent the sea water inflow by a grout curtain. The exploratory works should be done in phases:

- First phase: boreholes drilled at a distance of 4 m along the crest of the dam and grouted to a depth of 65 m BSL, then consolidation grouting of the karstified breccia below the dam from 10 m to 35 m BSL.
- Second phase: boreholes, in between boreholes of the first phase, drilled and grouted till 130 m BSL.
- Third phase: grout curtain below the road extended for 100 and later 200 m on both sides of the dam.
- Forth phase: additional grout curtains behind the smaller springs to the north if needed and a higher rise of the pool’s level. In all this exploratory phases a testing with a rise-spring-level to be made, the results analyzed and the next phases adjusted. A 4 m rise enables the existing dam (Breznik, 1998).

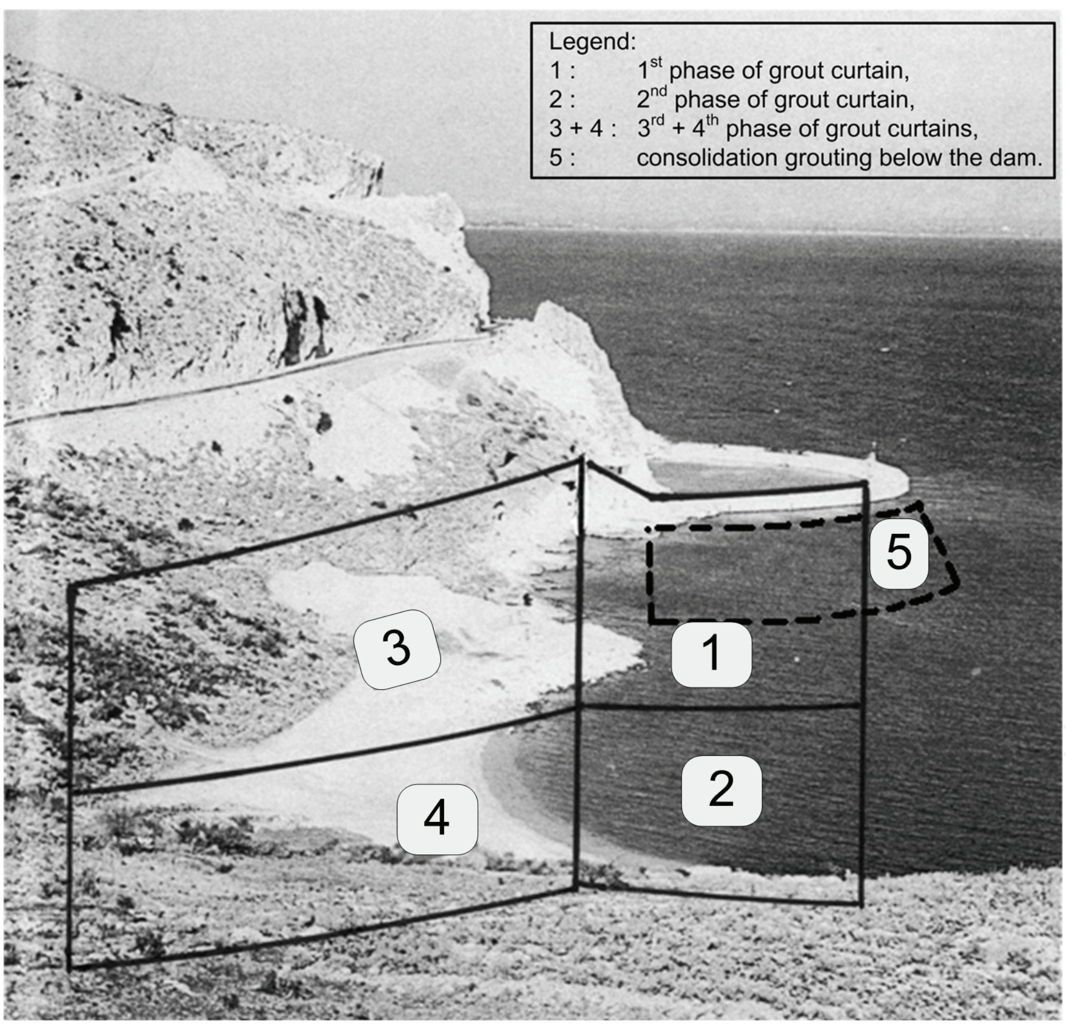


Fig. 20. Kivery dam. Desalination structures proposed (photo Breznik, 1969; Breznik, 1998; Breznik & Steinman, 2008).

This is a general proposal for exploration activities and they should be adapted to the partial results obtained. A final success with a 70% probability is to desalinate spring's water to 50 mg/l Cl^- in dry periods, and a 90% probability in wet periods.

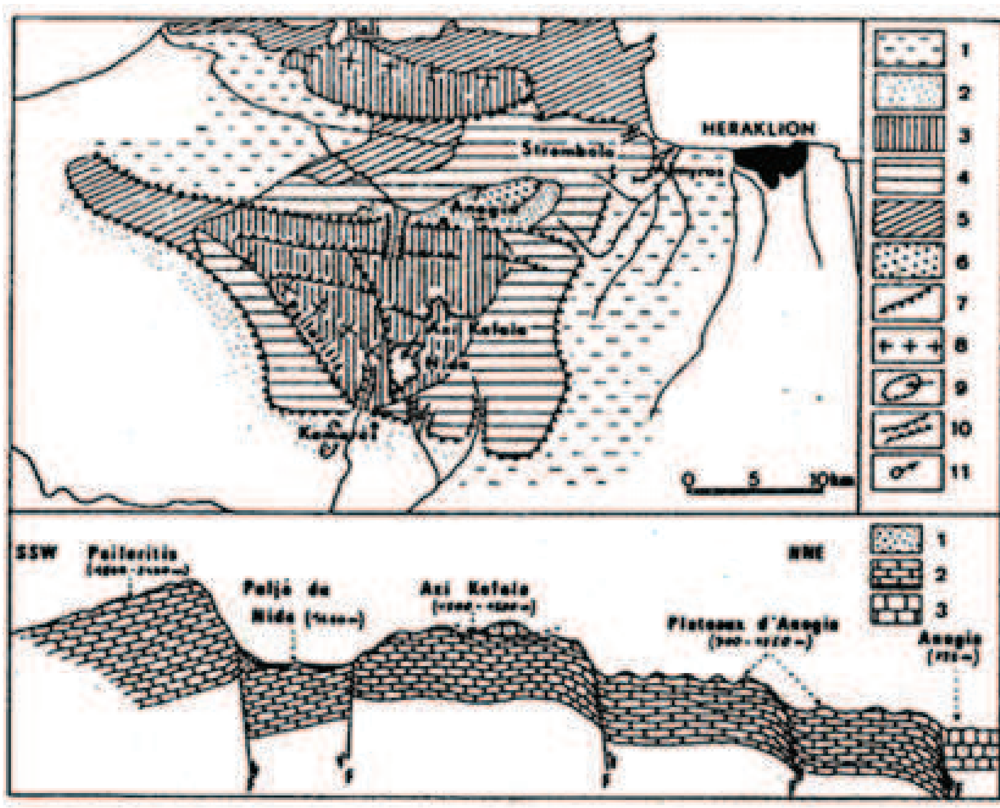


Fig. 21. Morpho-structural sketch of the Psiloritis massif and the Psiloritis-Anogia geological section with Almyros Irakliou and Bali springs (Bonnefont, 1972).

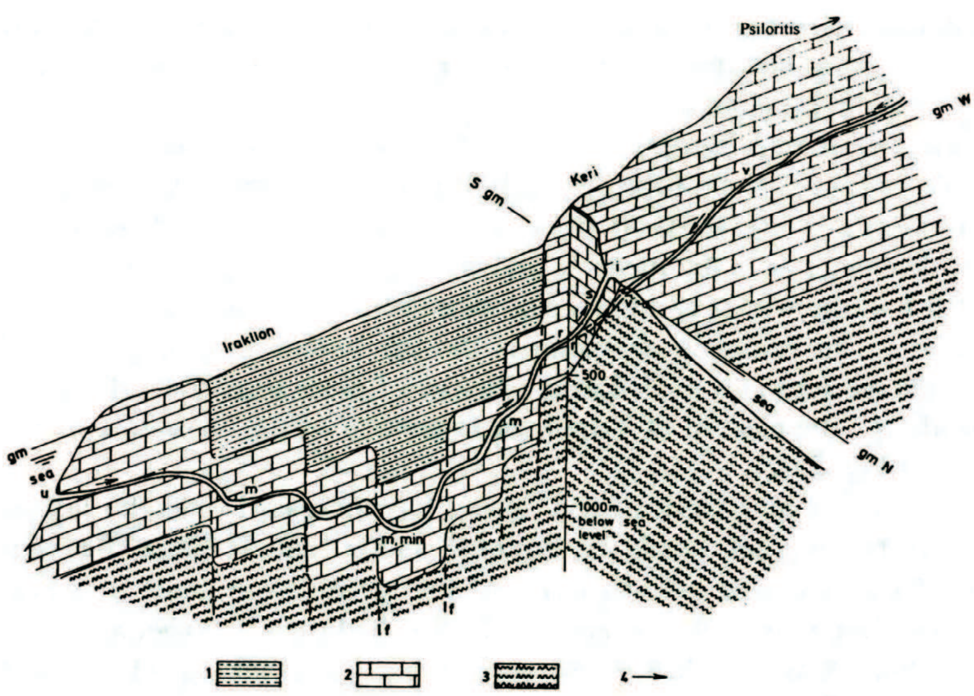


Fig. 22. Almyros Irakliou spring in Greece. Schematic geological block diagram with the supposed disposition of the spring veins in the conduit-flow karstic aquifer (Breznik, 1978).

4.5 Almyros Irakliou brackish spring in Greece

The characteristic of this spring, at 1 km from the sea coast, with many primary veins, of a 300 km² karstic recharge area and with very deep vein-branchings at differed depths, is a very slow increase of the salinity during a decrease of the discharge (Ré, 1968; Fig. 6; Breznik, 1971; 1973; 1998; Breznik & Steinman, 2008; Monopolis et al., 2005; Panagopoulos, 2005; Soulios, 1989).

All the veins are in Mesozoic limestone and the lower veins below the Festos-Irakliou graben filled with Neogene deposits. This spring was investigated by the United Nations - UNDP-FAO and Greek Government in the years 1967-1972. Between the spring and sea coast 15 deep boreholes, with a mean depth of 240 m, were drilled, with the aim to find, and to seal with a grout curtain, a conduit with sea water inflow. The result of investigation was that this conduit is not between the nearest sea and the spring, but is below Neogene deposits at about 800 m BSL and about 14 km long.

Almyros spring has a mean discharge of 8 m³/s, a temperature of water 16° C and had a tritium content of 45 T. U. of samples taken in August 1969, analyzed at IAEA in Vienna.

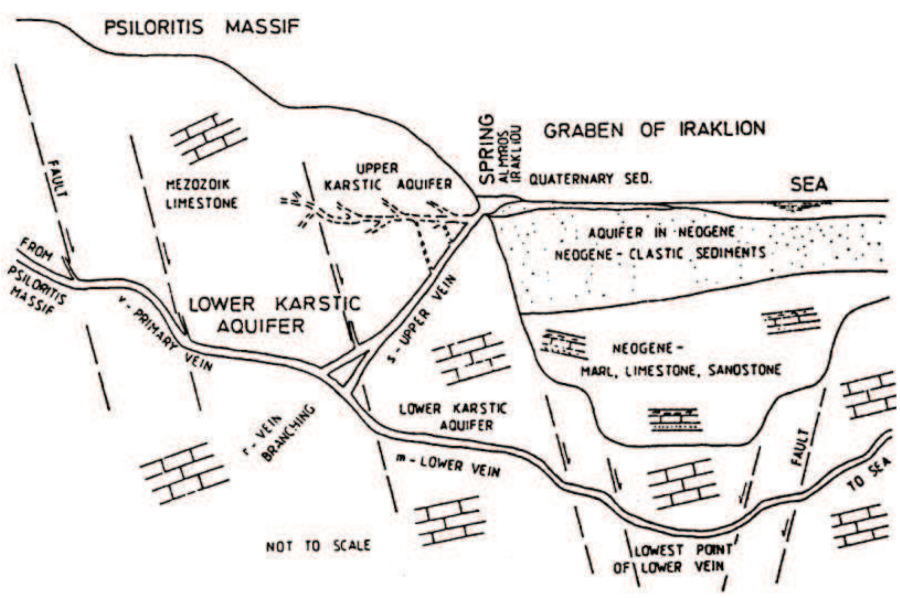


Fig. 23. Almyros Irakliou brackish spring. Main aquifers of the Psiloritis and Keri massifs and of the Irakliou graben (Breznik, 1984; 1998).

Precipitations at Rhodos island had 1100 T.U. in 1963, 200 T.U. in 1964 and 50 T.U. in 1969, while in Ljubljana 120 T.U. in 1975, what confirms a large volume of the Psiloritis underground storage and a slow, many years lasting outflow of precipitations. A week aquifer in Neogene deposits had a discharge of 0,12 m³/s, a temperature of water 19-20° C and 19-13 T. U. in the same period (Breznik, 1971).

We proposed to explore the desalination of the Almyros spring by the isolation, rise-spring-level and interception methods. A 10 m rise of spring level was proposed (Breznik, 1971). A new dam was constructed (1976) and spring level was raised at 10 m ASL for some month in 1977 and 1987. Spring water remained brackish (negative result) but the discharge diminished only slightly and no estavelles appeared in the Irakliou Sea (positive results). We concluded that a higher elevation of the level should be determined by a winter test with a larger discharge of water (Breznik, 1978), proposed a 20 to 30 m rise (Breznik, 1984) and calculated a 28,76 m, however with uncertain data (Breznik, 1989).

4.6 Rise-spring-level method of the development

This method requires a siphon shaped lower vein. Almyros has indeed a very deep lower vein, formed by a gradual subsidence of the Festos-Irakliou graben. We propose a 25 to 35 m ASL spring level with a construction of an underground dam.

The exploration phases with testing are: First phase: excavate a shaft, of 8 m diameter, with reinforced concrete lining, from surface to 5 m ASL with 2 table valves; drill interception wells into the main karst conduit till 30 m BSL; excavate 2 bottom outlets, of 5 m^2 with reinforced concrete lining, with valves at the outlets; seal the conduit with a concrete plug and a consolidation grouting. Raise the spring level, register the salinity and locate water losses. Second phase: construct a grout curtain of one row boreholes at a 4 m distance, till a depth of 80 m BSL. Raise the spring level and register the results. Third and other phases: condense and extain the grout curtain, with boreholes at 2 m distance, till a depth of 120 m BSL, construct a small dam around an expected overflow karst spring in the Keri ravine. Raise the spring level to 25-35 m ASL. When the salinity is below 50 mg/l CI and losses of water are small the exploration phases are completed. We expect, with an 80% probability, a safe yield of fresh water of about 2 m^3/s in dry periods and a 90% probability of fresh water in wet periods.

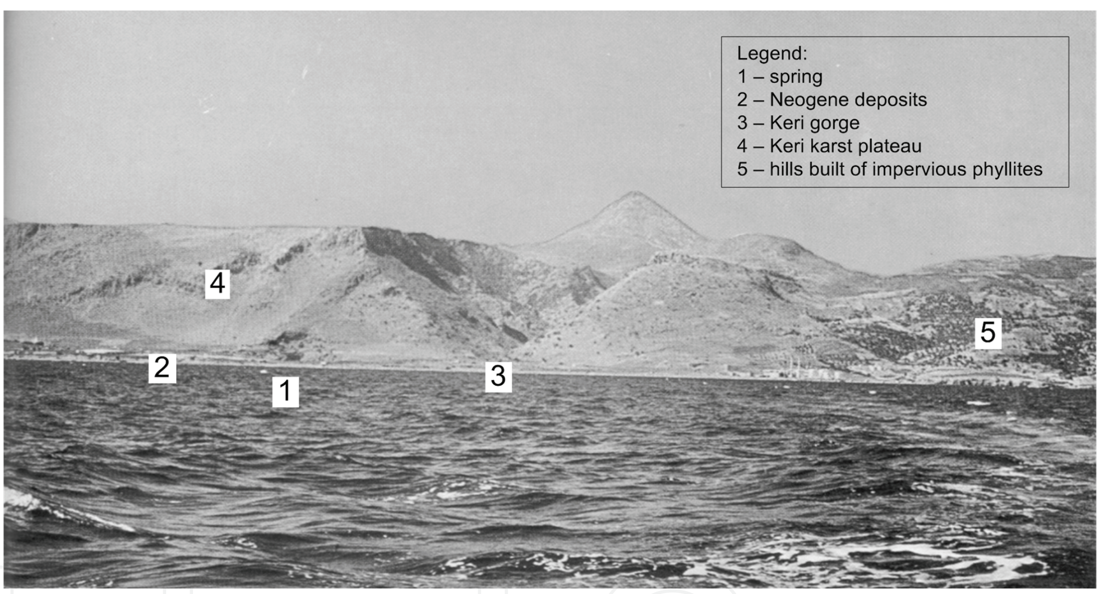


Fig. 24. View of the Almyros Irakliou spring area (photo Breznik, 1970).

The main object of the underground dam is the concrete plug with grouting (No. 5 in Fig. 25). The ground water flow through the place of the proposed plug could be blocked, by diverting the flow through the extended bottom outlet (No. 3), bellow the 1976 dam. This is achieved by raising the water level of the spring pool to about 6 m ASL, by regulating the water valves of the 1976 dam. Down flow of the fresh concrete into the steep main karst conduit (No. 1), could be prevented by a downside planking of the plug.

The first possibility is a planking of closely drilled boreholes of 60 m depth, of 30 cm diameter with casing filled with concrete. Two to three additional boreholes with pipes will enable pumping of concrete from the surface.

The second possibility is a new access shaft of 3 m diameter and 45 m depth at a 10 m distance upstream from the plug. Divers have to construct steel planking and install pipes for pumping concrete from a surface to a depth of about 25 m below water level. Constructors could propose other solutions.

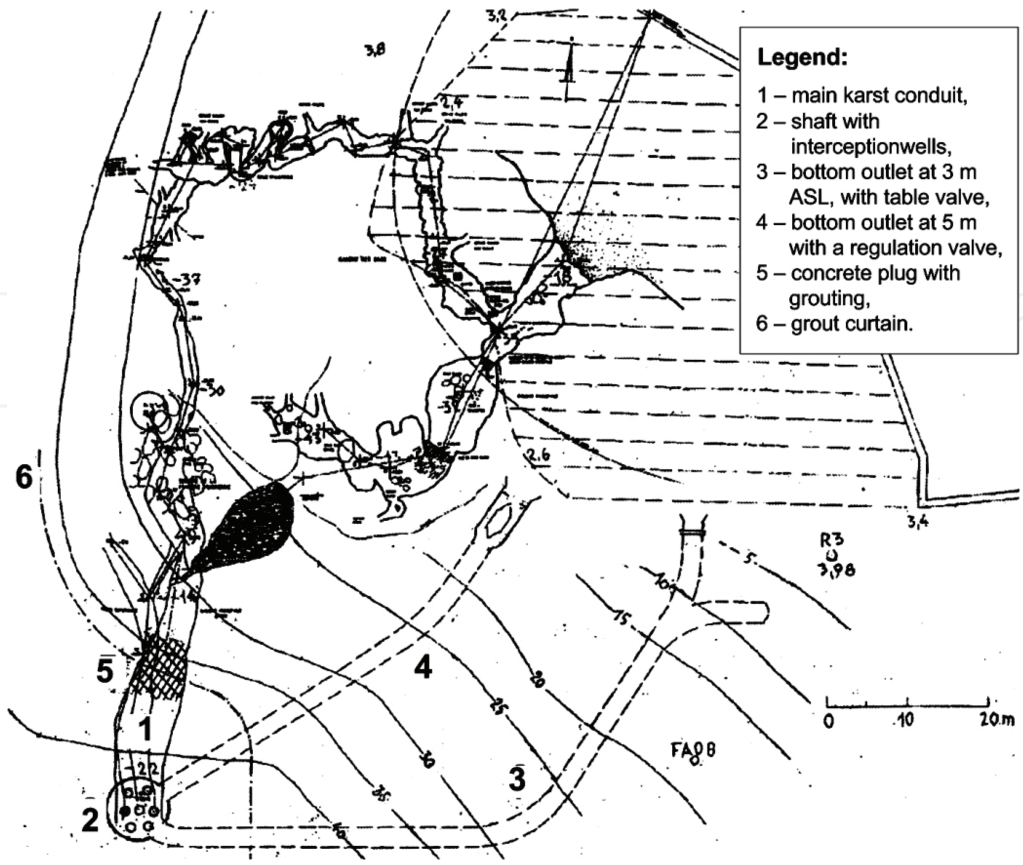


Fig. 25. Structures for the exploration phases of the desalination of the Almyros brackish spring by the rise of the spring level with an underground dam (Breznik & Steinman, 2008). Map of karst conduit (Barbier et al., 1992).

The structures for the final exploitation of fresh water are: Spillway for the high water outflow, small hydropower station for the regulation of the required water level for the desalination and for the production of the electricity, fresh water pipeline to Iraklion. Hydropower stations regulate the level of water in the irrigation canal along the Durance River in France. Rise-spring-level method could desalinate also ground water of the Keri, Tylissos and other low altitude areas. The existing Iraklion power station could be cooled by hyperbolic cooling towers used in Europe, or by sea water pumped out of deeper layers, used for cooling nuclear power stations in Japan. This unique desalination plant will be very attractive for tourists in Crete and should be economically exploited by the presentation of the underground hydrogeology, of the desalination structures and the restoration of the old scenery with mills (Breznik & Steinman, 2008).

4.7 Interception method of development

In the years 1968-1971 were the piezometric levels of fresh water in the Gonies area in boreholes at about 44 m ASL at the distance of 8 km from the Almyros spring and in the Koubedes-Tylissos area in the boreholes at about 29 m ASL, at the distances 3-4 km (Breznik, 1971; 1973; 1990; 1998; Breznik & Steinman, 2008). The municipal DAYAH Company had drilled 40 deep wells in the areas Keri, Tylissos, Gonies and Krousonas at 13 km since 1987. In the year 2000 fresh water was pumped out of 17 deep wells (Arfib, 2000). A normal consequence of a pumping many years out of coastal aquifers is a decline of the piezometric surface and the inflow of sea water. In Tylissos area the piezometric surface declined from about 29 m in seventies to about 15 m in 1997 and induced a salination of wells (Monopolis et al., 1997; 2005).

The important question is now; could water of wells in the Gonies and Krousonas areas remain fresh? Ground water of these areas flows to Almyros spring through a very deep vein-branching at 800-1000 m BSL, where is a fresh water outflow and a sea water inflow which depends upon the piezometric surface of fresh water. An expected overpumping of the Gonies-Krousonas wells, due to the loss of the Keri-Tylissos salinated wells, will lower the fresh water piezometric surface and induce a sea water inflow. Only moderate pumping yields could prevent the salination of this water. An over pumping of Malia wells will have similar consequences (Breznik & Steinman, 2008).

5. Conclusions and recommendations

Many desalination methods were proposed and many scientific papers published but, the important Greek springs: Bali, Kiveri and Almyros Irakliou, are still brackish after 30 years of attempts. In a karst underground are so many unknown data, needed for a mathematical ground water model, that the results are not reliable. We propose to achieve the desalination with physical-field tests: by the isolation method for the Bali and Kiveri springs with grout curtains and by the rise-spring-level method for the Almyros Irakliou spring with an underground dam. We estimate there are 70-80 % probabilities of the success in dry periods and 95% for Bali and Kiveri and 90% for Almyros Irakliou springs in wet periods.

The Dragonja river storage reservoir with 20 - 30 millions m^3 of fresh water pumped out of Rižana river, could solve water shortage of SW Slovenia. The Intergovernmental Panel on Climate Change (IPCC) warns about still smaller precipitations and higher temperatures in the Southern Europe in the future. So, the supply of fresh water will become increasingly important.

The proposed methods are intended to intercept fresh water before it is mixed with salt water, allowing the accumulation of water in wet seasons. No doubt, proposed solutions require greater initial investment, but have low operating costs. Besides, water supply is not exposed to the imported high-technology and is not high energy demanding.

We reserve author's rights for the proposed desalination methods and structures (Breznik, 1998; Breznik & Steinman, 2008).

6. Glossary

Admissible salinity: The quantity of salts in drinking or irrigation water which is harmless to people, animals or vegetation. Slovene and other countries' standards for drinking water is 250 mg/l of Cl^-. In dry areas drinking water with 500 mg/l of Cl^- is considered as harmless. Many villages in the Mediterranean area use water with more than 500 mg/l of Cl^-, the Bedouins of the Sahara up to 2000 mg/l of Cl^-.

Aerated zone: Zone above ground water surface in which karstic pores are filled partially with air and partially with water.

Aquifer: A formation, group of formations or part of a formation that bears water which is not bound chemically or physically to the rock.

Brackish spring: General term which means a spring with brackish water but also the vein and a place of such a spring.

Brackish water zone (also called zone-of-mixing or transition zone): Part of aquifer saturated with brackish water.

Doline: A depression that has a funnel-shaped hollow with a diameter of 10 to 100 m, formed by the dissolving of limestone or dolomite. It is an international term. The local term is vrtača, the English term being sinkhole.

Drowned zone: Zone below ground water surface in which karstic pores are saturated with water.

Equilibrium plane: Nominal plane in a karst of anisotropic permeability connecting those points of veins and branchings where the water pressures from fresh water and sea water sides are equal.

Fresh water zone: Part of aquifer saturated with fresh water.

Interface: The surface bordering the fresh water and sea water in an aquifer of isotropic permeability. This border could be sharply defined but is usually a transition zone.

Karst aquifer of anisotropic permeability: Karst region with isolated karstified zones with unkarstified blocks between them. Ground water moves along veins or conduits, which means along well-karstified zones. The aquifer is highly permeable in the direction of veins, but poorly permeable or impermeable in the transverse direction. Ground water movement is similar to the movement of water in a system of pipes which are not densely disposed, known as 'conduit type circulation'.

Karst aquifer of isotropic permeability: Karst region with many solution fissures, small channels which are all well connected in all directions. Movement of water is possible in all directions and is analogous to the ground water movement in granular sediments, known as 'diffused type circulation'.

Karstic ground water, karst aquifer: Water which fills karstic pores and veins in the drowned zone and is not bound physically or chemically to the rock.

Polje: An international term that refers to the largest karst hollow with a flat floored linear depression. In its typical form it has a steep side and steep circumference.

Ponor: This is the largest entry in the base or in the side of the polje in which water flows, an international term. Schwinde (Ger), swallow hole (Eng) and perte (Fr).

Salinity: Quantity of salts in water. In this paper expressed as content of chlorine ions (Cl^-) in mg/l. The salinity of the Mediterranean Sea is about 21000 mg/l of Cl^-.

Sea estavelle: A submarine spring with fresh water which ceases to flow in each dry season and starts to swallow sea water.

Sea ponor: Hole in the sea bottom or seashore which swallows sea water.

Sea water zone: Part of aquifer saturated with sea water.

Storage coefficient of the karst is the volume of water which a karstic aquifer releases from storage or takes into storage.

Submarine spring: A spring with either fresh or brackish water rising from the sea bottom.

Uvala: A coalescence of two or three dolines, an international term.

Vein or conduit: General term for a zone which is highly permeable in the flow direction and poorly permeable or impervious in the transverse direction. Ground water moves through veins in a karst of anisotropic permeability. The form of the vein is undefined; it could be a solution channel, a permeable fissured zone, a system of small connected cavities, etc.

Vein-branching or branching: The place where the primary vein branches off into a lower vein, connected with the sea, and an upper vein, leading to the spring.

7. Acknowledgments

We thank the Governments of Slovenia, Croatia, Montenegro, Greece and Turkey for the presentation of their unpublished investigation results.

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Desalination, Trends and Technologies
Edited by Michael Schorr

ISBN 978-953-307-311-8
Hard cover, 334 pages
Publisher InTech
Published online 28, February, 2011
Published in print edition February, 2011

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Marko Breznik and Franci Steinman (2011). Desalination of Coastal Karst Springs by Hydro-geologic, Hydro-technical and Adaptable Methods, Desalination, Trends and Technologies, Michael Schorr (Ed.), ISBN: 978-953-307-311-8, InTech, Available from: http://www.intechopen.com/books/desalination-trends-and-technologies/desalination-of-coastal-karst-springs-by-hydro-geologic-hydro-technical-and-adaptable-methods

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